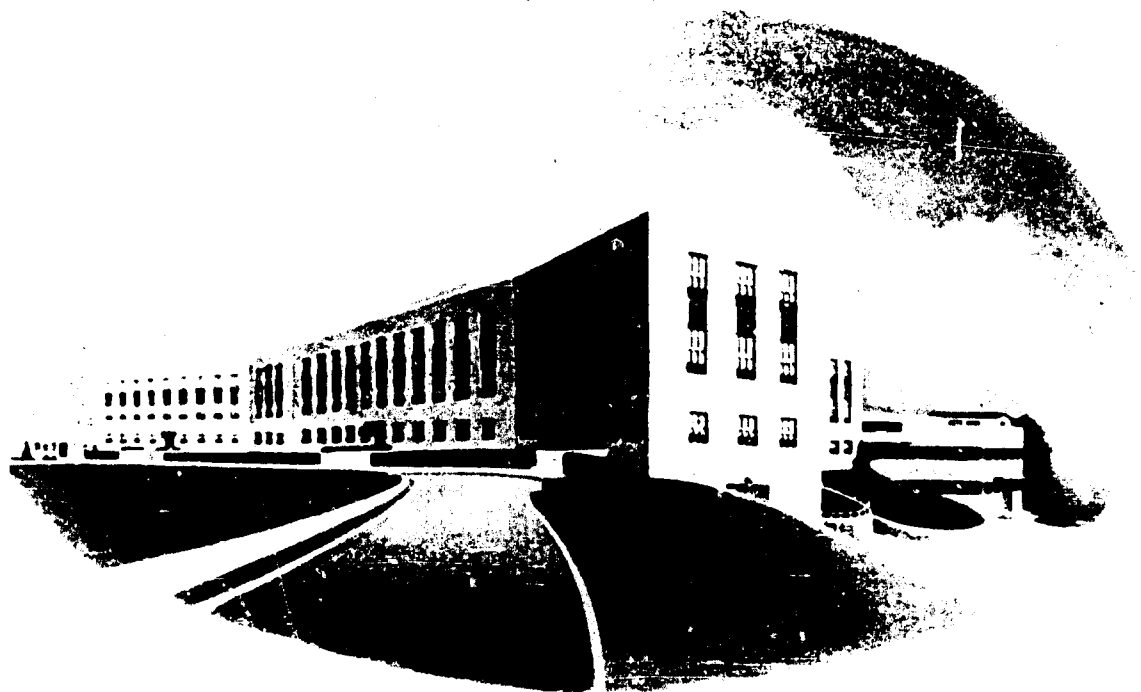


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NAVAL MEDICAL RESEARCH INSTITUTE



THERMAL PROTECTION DURING IMMERSION IN COLD WATER

RESEARCH REPORT

MR 005.13-4001.06

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BETHESDA, MARYLAND**

27 March 1964

SUMMARY

The physical principles which pertain to heat loss from the human body when immersed in water at lower temperatures than its own, together with the physiological mechanisms which are activated in maintaining thermal balance are reviewed and related to the problems of thermal balance of underwater swimmers. Data on the amount of heat lost under various conditions of water temperature, body insulation, and rates of heat production are presented. The limited effectiveness of increasing internal and external body insulation is established by this data.

The proposal of a method to counteract the body heat loss of underwater swimmers by the use of electrical resistance clothing is presented as being feasible within the present state of the art of battery and blanket manufacture.

Presented at the Second Symposium on Underwater Physiology,
Washington, D. C., 25-26 February 1963.

Published in the Proceedings of the Second Symposium on Underwater Physiology,
Publication No. 1181, National Academy of Sciences - National Research Council,
Washington, D. C., 1963, pp. 247-266.

Issued by the Naval Medical Research Institute

THERMAL PROTECTION DURING IMMERSION IN COLD WATER

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If the popular reports of the long distance swimmers doggedly "crawling" across the English Channel with water temperature at 60° F and stories of frogmen going swimming at the North Pole were interpreted literally, then one might assume that body heat loss is no longer a problem for underwater swimmers. Fortunately, we are all sufficiently biased by our own experiences with cold that any such reports are tempered with some skepticism. In fact, there is still much to be learned about the effects of immersion in cold water upon human physiology and performance.

Extensive research has been carried out in the field of thermal protection during exposure to cold air. However, research into the problems of thermal protection during immersion in cold water has been limited. The difference in the rates of heat loss in air and in water causes significant differences in the physiological effects of exposure to cold air and immersion in water at the same temperature.

It is common knowledge that standing nude in a normally heated room with the air temperature at 72° F does not immediately make one feel cold. However, diving into a swimming pool with the water at the same temperature immediately makes one feel very cold and causes a rapid loss of body heat with a decrease in skin and deep body temperature and the onset of hypothermia. Hypothermia may be considered to be a condition in which the deep tissue or "core" temperature of the body is below the normal physiological range, about 97° F or 36° C, and is the temperature at which malfunctions in normal physiology begin to occur.

There is a good explanation for these observations. Water has a specific heat approximately 1000 times greater than that of air so that each cubic centimeter of water adjacent to the skin can take up a thousand times more heat from the body than a comparable volume of air for a given increase in temperature. In addition, the thermal conductivity of water (or rate of transfer of heat by conduction) is some 25 times greater than that of air. During immersion, body heat is therefore rapidly conducted away from the skin into the adjacent layer of water. The rate at which heat is conducted from the immersed human body is so rapid that heat loss is limited primarily by the rate at which heat is transferred by the blood from the central core of the body to the skin. For this reason, thermal balance of the human body when at rest in water can only be attained if the water temperature is 95-96° F.

The rate of heat loss from the immersed human body is of the utmost importance to people who are immersed for long periods of time, i. e., distance swimmers, skin divers, underwater swimmers, hardhat divers, and survivors from disasters at sea. The danger to swimmers from hypothermia is not generally

recognized. The body cooling which swimmers and divers experience has been considered to be a sign of poor physical condition or weakness and their "esprit de corps" demanded that complaints about the effects of the cold be minimized. Since hypothermic anesthesia has become clinically useful, the effects of hypothermia have been more accurately studied and quantitated. McQueen⁽¹⁾ noted that although the deep body temperature at which given central nervous system changes occur varied with different individuals, in general, when the temperature of a human being subjected to hypothermic anesthesia had decreased to 34° C (94° F) amnesia occurred for the period of cooling below that temperature. The patients likewise became dysarthric, and began to lose contact with their surroundings. Pain was generally appreciated down to about 30° C (86° F) when the ability to recognize relatives or surroundings had also been lost. Voluntary motion was lost at 27° C, as were the pupillary light reflexes and deep tendon and skin reflexes. Virtue⁽²⁾ corroborated these observations and noticed that between the temperatures of 30° C and 32° C cardiac irregularities occurred, such as atrial fibrillation, ventricular ectopic beats, and ventricular rhythms.

Similar observations have been recorded from the Dachau experiments⁽³⁾. Loss of consciousness was reported to occur at 30° to 32° C. Therefore, should a swimmer, either intentionally or through necessity, stay in the water long enough to decrease his deep body temperature to below 34° C he would have little recollection of events that followed and would be incapable of carrying out purposeful actions. His operational usefulness would have ceased, and should his body temperature have decreased to 32° C, it is probable that cardiac irregularities would terminate his operational mission. In addition to these more serious sequelae of heat loss from the body core, the effects of regional heat loss upon the function of the fingers, hands, and arms has been found to be a limiting factor in immersion tolerance. Provins and Clarke⁽⁴⁾ have demonstrated that as the fingers, hands and arms cooled below 60° F (15.5° C) their subjects developed an increased reaction time, a decrease in tracking proficiency, a decrease in manual dexterity with a loss of tactile discrimination and kinesthetic sensation, as well as a decrease in muscle strength. In our immersion studies conducted at 50° F, some subjects demonstrated a decrease in grip strength of down to 50 per cent of normal after one hour of immersion. The deep-body cooling rates of our thin, nearly nude subjects were from 6 to 9° F/hr when immersed to neck level in water at 50° to 60° F. At these cooling rates the difference between 60 minutes and 75 minutes of immersion could easily mean the difference between consciousness and unconsciousness. Observations on the respiratory and cardiovascular response to immersion in water have also been reported⁽⁵⁾. A review of the physiological responses of the body which limit the heat loss from immersion in cold water, therefore, seems warranted.

The thermostatic neuroregulatory mechanisms of the human are extremely sensitive to specific local temperatures of receptor structures. The capacities for heating and cooling of the human system are so adequate that changes in deep body temperatures of more than 1° C are rarely experienced by any of us in good health, even though the heat generating systems or heat dissipating systems vary their operating load by a factor of 10. If, in any period, heat production and heat loss from the body are not equal, the difference D , will change the average temperature of the tissues of the body, by the equation:

$$D = M - H = \frac{ms}{S} \times \frac{d\theta}{dt}$$

in which M and H are the heat production and heat loss respectively, in kcal/sq m/hr; m is the mass of the body; s its specific heat; S is the surface area of the body; and θ is the mean temperature of the body in ° C. From this equation, the rate of change of the average body temperature will be in ° C per hour⁽⁶⁾.

Although theoretically the quantity of heat in the body at any time could be determined from the "mean" body temperature, the mass of the body, and the specific heat, it is practically impossible to obtain an accurate value for θ . As a result, extensive simplifying assumptions are made so as to adjust the theory to experimental data. When experiments are made in air, a mean skin temperature is obtained by a mathematical weighting scheme which has been adjusted to fit experimental data. When experiments are done on body immersion, the simplifying assumption is made that the skin temperature equals the water temperature. Obviously, if the Newtonian concepts of thermal transfer obtain, this assumption is erroneous, and may be responsible for the introduction of considerable error in measurements of thermal conductance of the skin.

Deep body temperature measurements from the rectum, esophagus or tympanic membrane are more reliable than the skin temperature, which varies significantly in different parts of the body, and is lower in the dependent portions of the body, i. e., feet, lower legs and hands, but approximates deep body temperature when measured in the armpit or skinfolds.

It may be assumed for the purpose of analysis, that a man of average weight (70 kilograms or 154 pounds) would have an average specific heat of 0.83¹, even though the specific heat of the human body varies to some extent and is dependent upon the per cent composition of muscle, bone, and adipose tissue. This implies that for a 70 kilogram man, an imbalance in body heat exchange of 58 kilogram calories (kcal) would result in a change in body temperature of 1° C. If a thermal imbalance of the body resulted in a loss of heat of only 232 kcal, the mean body temperature would be decreased from 37° C to 33° C where cerebral dysfunction would occur. When one reflects that this 70 kilogram man at rest generates 70 kcals of heat per hour and that, when vigorously working in a hot or cold environment, he may generate or lose 5 to 10 times this amount of heat in one hour, then the effectiveness of thermal balance in the human body can be appreciated.

Under ordinary conditions the heat loss from the body in air may be formalized with the following equation:

$$H_n = H_c + H_d + H_e + H_r$$

¹The specific heat of a substance may be defined as the ratio of the thermal capacity of the substance (quantity of heat necessary to produce unit change in temperature in unit mass of the substance) as compared to the thermal capacity of water, at 15° C.

in which H_n is the total heat loss of the body; H_c is the heat lost by convection; H_d is heat lost by conduction; H_e is heat lost by evaporation; and H_r is heat lost by radiation. In considering the problem of thermal balance of the underwater swimmer or of the human immersed in water up to neck level, it is possible to eliminate the terms of H_r and H_c , inasmuch as there are essentially no heat losses by radiation and convection from the body in water.

There is also no evaporation from the skin of the immersed body. H_e or the evaporative heat loss therefore is limited to the amount lost by evaporation from the alveolar surface of the lungs, plus the heat required to warm the inspired air to body temperature, and the heat required to increase the water vapor content of the air up toward 100 per cent. This quantity of heat is lost to the body on expiration. It has been variously estimated by different investigators. Carlson et al⁽⁷⁾ used 24 per cent of the total body heat generated as the pulmonary loss. Bribbia et al⁽⁸⁾ measured the heat loss of vaporization from the lungs of men exercising in the Arctic to be 9 per cent of the total heat expenditure and also demonstrated that the water vapor loss was proportional to the ventilation rate. These values are in close agreement with Day's approximations for heat of vaporization⁽⁹⁾.

The heat required to warm the air used in respiration may be readily calculated if it is assumed that the temperature of the expired air is constant at 37° C. The temperature of the expired air decreases with the drop in the deep body temperature and with increased ventilation rates. Although this assumption is inaccurate, it is sufficient for these calculations:

TABLE I

Heat Lost from the Lungs at Various Air Temperatures* After Day⁽⁹⁾

Air Temperature °C	Heat Lost to Air kcal	Heat Lost Through Vaporization kcal	Total Heat Lost kcal
37.5	0.00	7.77	7.77
20.0	2.87	12.27	15.14
0.0	6.16	14.78	20.94

*The values are kilocalories per hour, and the assumption is made that the relative humidity is 50 per cent, and the respiratory rate is 600 liters of air per hour.

In our studies on immersion in water at temperatures from 35° C to 10° C and with air temperatures of 20 to 23° C and relative humidity of 40 to 55 per cent, the respiratory minute volumes of our subjects varied from a minimum in warm water of 400 liters per hour to a maximum in cold water of 3000 L/hr. Day used a mean value for respiratory volume of 600 L/hr so that the heat loss from the

lungs of our subjects would have varied from approximately 10 to 100 kcal/hr. The total heat generated by our subjects as determined by oxygen consumption⁽¹⁰⁾ varied from 65 to 600 kcal/hr. The heat loss from the lungs of our subjects would have been approximately 15 per cent of the total heat generated and this is significantly less than the 24 per cent used by Carlson.

The greatest amount of the heat lost during immersion is therefore due to Newtonian cooling, i. e., conduction of heat from the warm body to the cooler surrounding water. The heat loss from the body via conduction may be expressed by this formula:

$$H_d = 5.55 \frac{A(T_c - T_w)}{I_s + I_c}$$

in which H_d is equal to the heat lost to the environment via conduction in kcal/hr; T_c is equal to the core temperature of the body in °C; T_w is equal to the water temperature in °C; A equals the immersed surface area of the body in square meters; I_s is the thermal insulation of the skin and subcutaneous tissue in CLO²; I_c is the thermal insulation of the clothing in CLO; and 5.55 is the conversion constant for converting the total insulative value into CLO.

In this equation, the water temperature is assumed to be equal to the temperature of the skin. This is an obvious over-simplification. Upon immersion, the skin temperature rapidly, but asymptotically, approaches but does not equal water temperature so that this approximation is reasonable. Furthermore, since the body "core" temperature T_c , can be limited to the temperature range in which the body function is normal, this term may also be made a constant. The surface area of the human body is constant for any given time, although change in surface area of 5 per cent results from a change in weight of 10 per cent.

The insulation of the external tissues of the body, I_s , is an important variable. The many-fold variations of the insulative covering of the body can be judged by references to Table II which lists values for thermal conductivity of the human body obtained by different investigators on obese and thin men immersed in water at different temperatures. The insulation of the body K_i , in °C/kcal/sq m/hr is the reciprocal of the thermal conductivity of the tissue, in kcal/sq m/hr/°C.

From this table it is apparent that tissue insulation of humans may vary 15 fold, under different conditions. The lowest thermal conductivity, 2.2 kcal/sq m/hr/°C (highest insulation), was found on an obese, long distance swimmer when his body insulation was measured while he was resting, immersed in a water bath at 10° C. This same individual had a thermal conductivity of 33 kcal/sq m/hr/°C when measured with the subject seated in a bath with a water temperature of 36° C. This difference in conductivity represents the difference of tissue

²CLO is a unit of insulation defined by Gagge, Burton and Bazett⁽¹¹⁾ which allows the heat transfer of 5.55 kcal/sq m/hr at a temperature gradient of 1° C.

TABLE II

Table Showing Value of Skin and Subcutaneous Tissue
Thermal Conductance of Different Humans

Tissue	Thermal Conductivity (kcal/sq m/hr/°C)	Reference
Human (obese) Resting in 10° C water	2.2	Carlson <u>et al</u> ⁽⁷⁾
Human (obese) (J. Z.) Resting in 16° C water	5.9	Pugh and Edholm ⁽¹²⁾
Human (obese) Resting 33° C water	9.1	Carlson <u>et al</u> ⁽⁷⁾
Human (thin) Resting 33° C, 24° C and 20° C water	9.1	Carlson <u>et al</u> ⁽⁷⁾
Human (thin) (G. P.) Resting 16° C water (Shivering)	12.7	Pugh and Edholm ⁽¹²⁾
Human (obese) (J. Z.) Swimming 16° C water	13.4	Pugh and Edholm ⁽¹²⁾
Human (thin) (G. P.) Swimming 16° C water	24.7	Pugh and Edholm ⁽¹²⁾
Human (obese) Resting 36° C water	33.0	Carlson <u>et al</u> ⁽⁷⁾
Fat <u>in vitro</u>	14.4 per cm thickness	Henriques ⁽¹³⁾
Muscle (wet) <u>in vitro</u>	39.6 per cm thickness	Henriques ⁽¹³⁾
Water	53.0 per cm thickness	CU SP Report ⁽¹⁴⁾

conductivity with maximum vasodilation (at 36° C) and maximum vasoconstriction at 10° C. Carlson, et al⁽⁷⁾ demonstrated the changes in the tissue insulation of this obese swimmer at different immersion temperatures as can be seen on the uppermost line in Figure 1. The thinner subjects showed less temperature effect and the thinnest subject, represented by the bottom line of the graph, showed essentially no change in tissue insulation from 33° C to 20° C immersion temperatures. When the tissue insulation was plotted against the specific gravity and per cent obesity of these subjects, there was a linear relationship (Figure 2).

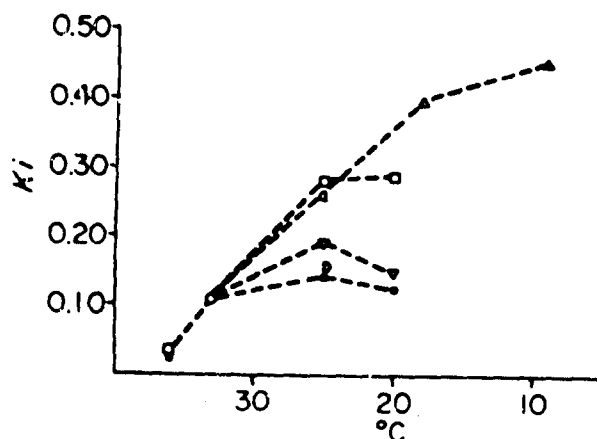


Figure 1. Body Insulation Calculated at Various Water Bath Temperatures. Each symbol is a separate subject. From Carlson *et al*⁽⁷⁾.

the equivalent conductance of adipose tissue (Table II) and found apparent insulation thicknesses of 73 mm at 10° C, 20 mm at 33° C, and 5 mm at 36° C. The measured skinfold thicknesses of this subject were: arms - 18.5 mm, chest - 18.5 mm and abdomen - 17 mm. This data would not only imply that adipose tissue is an effective insulator but that it is this adipose layer plus a layer of underlying muscle that functions in conserving body heat.

The effective insulation values of the skin and subcutaneous tissue shown in Table II are higher and lower than those generally quoted. Hardy⁽¹⁵⁾ gives the values of thermal conductivity of man as 6 to 9 kcal/hr/sq m/°C and as 5 to 8 kcal/hr/sq m/°C for women. These values represent measurements in air and in a body calorimeter but are in general not obtained under extreme rates of heat exchange such as those in Table II. Our own studies on immersion of subjects to neck level at water temperatures of from 10 to 34° C give values for thermal conductivity more in agreement with those in Table II. The 15 fold variation in effective body insulation, if accurate, suggests an explanation as to why the "fat man" can tolerate cold so much better than the thin man. The effectiveness of adipose tissue as an insulative layer in preventing body heat loss has also been demonstrated by Keatinge⁽¹⁶⁾. He immersed a group of subjects in 15° C water for 30 minutes and compared their body heat losses, as measured by rectal temperatures, with their adiposity or skinfold thickness. He observed a linear relationship between the amount of body heat lost and the reciprocal of the skinfold thickness, Figure 3.

These values for "external tissue shell" insulation have all been obtained by inference, i.e., the body oxygen consumption has been obtained and this value equated with equivalent heat generation. A percent of this heat value is assigned to the pulmonary evaporative loss discussed above, and the remainder is assumed to be lost to the water by conduction. Heat exchange from the head is also neglected. As discussed previously the 24 per cent loss may be excessive. Any errors would tend to give high thermal conductivities, but these errors would be consistent so that the determinations are of value for comparison. It is interesting to note that Carlson computed the apparent thickness of the insulative layer of his swimmer using

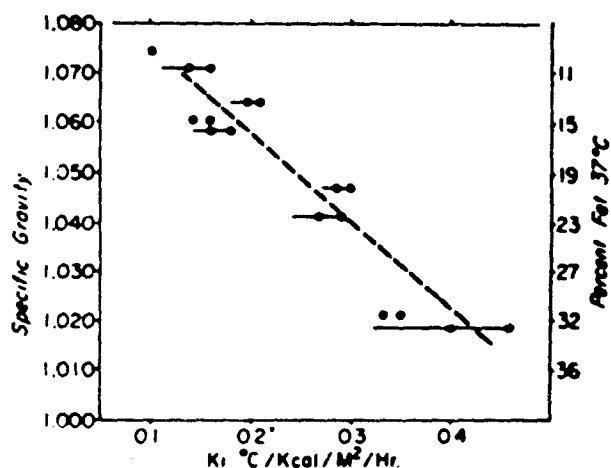


Figure 2. Maximum Values (solid circles) of Body Insulation Found for Various Subjects in the Water Bath. Average of several determinations (open circles). From Carlson *et al*⁽⁷⁾.

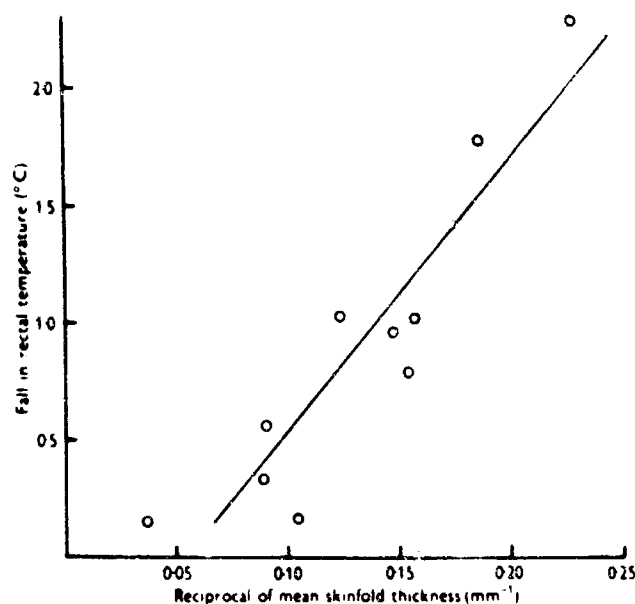


Figure 3. Relationship between Men's Subcutaneous Fat Thickness and their Fall in Rectal Temperature. From Keatinge⁽¹⁶⁾.

in one experiment in which the subject lay horizontal in the water with his neck and the back of his head immersed in water at 54° F, (12° C) the rectal temperature dropped to 70° F (26° C) in 70 minutes. Subjects exposed in this manner were found to have edema of the brain, increased cerebrospinal fluid pressure, and, in some cases, intracerebral hemorrhage. In our experiments, subjects have been immersed in 50° F water up to neck level for 60 to 90 minutes with a drop in rectal temperatures varying from 3 to 5° F, which implies that immersion of the head and neck induces a significantly greater heat loss.

The consideration of the "average" insulation of the body has one other disadvantage, in that it disregards the areas of the body where the insulation is anatomically poor, i.e., on all appendages, fingers, hands, toes, ears, nose, feet and male genitalia. The well-known difficulty which is encountered in providing adequate protective clothing for these parts of the body can be explained partly on the basis of poor insulation, and partly on the geometry of the parts. The equation for heat loss given above applies only to insulation on a plane surface. The rate of heat loss from cylindrical and spherical surfaces is also a function of the geometry. This problem received considerable attention during World War II when the operational theaters included the Arctic as well as the minus 55° C ambient temperature realm of the flyer. The theory which relates to the geometry of the heated body is beyond the scope of this paper. A complete analysis of the special problems of heat loss in the hands is given by van Dilla, Day and Siple⁽¹⁸⁾ and should be consulted for details. It is sufficient to point out that because of their geometry, the rate of heat loss from the fingers and other small appendages is so great that these areas of the body frequently limit exposure tolerance to cold when the skin and deep temperatures of the larger body masses are still within the comfort zone.

The calculation of skin thermal conductivity represents a mean value and implies that tissue conductivity is relatively uniform, and that the vasomotor response of the skin of the body is approximately the same throughout. Froese and Burton⁽¹⁷⁾ measured the heat loss from the human head and observed that the tissue insulation of the human head differs from that of the "mean" body insulation, and is relatively constant at 0.4 CLO when measured at air temperatures between -21 and 32° C. The rate of heat loss from the head therefore increased from 38 kcal/sq m/hr at 32° C to 340 kcal/sq m/hr at -6° C. Such measurements have not been reported on the immersed human head but the Dachau experiments⁽³⁾ support the thesis that the head is the most critical part of the body in protection against cold water. As an example,

Thus, it is apparent that there are only two principal physiological processes which limit the rate of heat loss from the immersed body: 1) evaporative losses from the lungs, and 2) conductive losses from the skin. The evaporative losses are relatively constant and directly related to the minute volume of respiration. The conductive losses, which are the more important, are limited by the factors which affect the thermal conductivity of the skin. These are the thickness of the adipose tissue with its regional variations, and the state of the vasculature of the skin which varies from maximum vasodilatation with maximum conductivity, to maximum vasoconstriction with minimum conductivity. The "average" thermal conductivity of the skin may vary 15 fold. When these extremes of conductivity are inadequate to control the rate of heat loss, some additional physiological regulatory mechanisms are utilized.

When mechanisms to prevent heat loss are inadequate the body will attempt to compensate by increased heat production. At immersion temperatures of 35.7°C (96°F), the so-called neutral temperature for baths, the basal metabolic heat production balances the body heat loss and maintains thermal equilibrium without surface vasoconstriction. At immersion temperatures below this, some increase in either heat production or tissue insulation is required. The increase in tissue insulation achieved by vasoconstriction has been shown to be limited, and therefore, must be augmented by an increased heat production, either by shivering which can increase heat production to 5-7 times basal or by purposeful work such as swimming, which can increase it up to 10 times basal. Unfortunately, the length of time that such high energy work can be continued is limited. Even trained long distance swimmers can only maintain a heat output of $275\text{ kcal/sq m/hr}^{(7)}$ to $310\text{--}350\text{ kcal/sq m/hr}^{(12)}$ for 10-12 hours. Trained frogmen are expected to be able to maintain a heat output of $200\text{ kcal/sq m/hr}^{(14)}$. Damage to human tissue occurs below 55°F (13°C) so that local skin temperatures must be kept above this temperature. In the appendages, intrinsic heat production is so minimal that skin temperature can only be maintained by an increase in convective heating produced by local vasodilation. However, the vasodilation of cold is considerably influenced by the general thermal balance of the body. Speakman⁽¹⁹⁾ made direct measurements on the blood flow in the hand at different water bath temperatures and showed a decreased blood flow with decline of water bath temperatures to 50°F (10°C). Below this temperature there was a striking increase in hand blood flow, which was frequently as large as at a water temperature of 95°F . If, except for the hand, the subject was comfortably warm, alternating vasodilation and vasoconstriction occurred ("hunting"). If the subject was chilled, the degree of increased blood flow was reduced. If the subject was uncomfortably warm, the blood flow in the hand remained high even in water at 10°C (50°F). Therefore, it would seem that the general body heat balance must be maintained before the local vasodilation of the fingers can be mobilized to provide heat to the fingers.

Since long distance swimmers have made an effective adaptation to swimming in cold water, it is appropriate to evaluate their particular adaptation. Pugh and Edholm⁽¹²⁾ have studied the temperature regulatory mechanisms of channel swimmers. The studies which they did on a channel swimmer and an amateur swimmer are illustrative, not only of the significance of body insulation, but also of the futility of man's plight in cold water. Figure 4 shows the silhouettes of these two subjects. One, J. Z. was short and thick, the other, G. P. was

tall and thin. J. Z. was a professional channel swimmer who had distinguished himself in these races prior to these studies. During the course of this study, J. Z. swam in a 10 mile race in Lake Windermere, England, when the water temperature was 16° C. He had no decrease in deep body temperature (rectal) as seen in Figure 5. However, when he was immersed to neck level in water at 16° C but was not swimming, his deep body temperature was seen to decline, although he did not overtly shiver. Also in Figure 5, the response of the tall thin subject G. P. can be seen under similar circumstances. G. P.'s body temperature dropped precipitously from 37° C to below 34° C when he swam for 30 minutes in Lake Windermere. He began to shiver after swimming for 15 minutes and his muscles became progressively weaker so that he could neither swim nor use his muscles to maintain his body heat. He became incapacitated and had to be helped from the water. This same subject, when placed in a tub of cold water lost body heat at approximately twice the rate of his "thicker" counterpart J. Z. under similar circumstances. In Figure 6, the

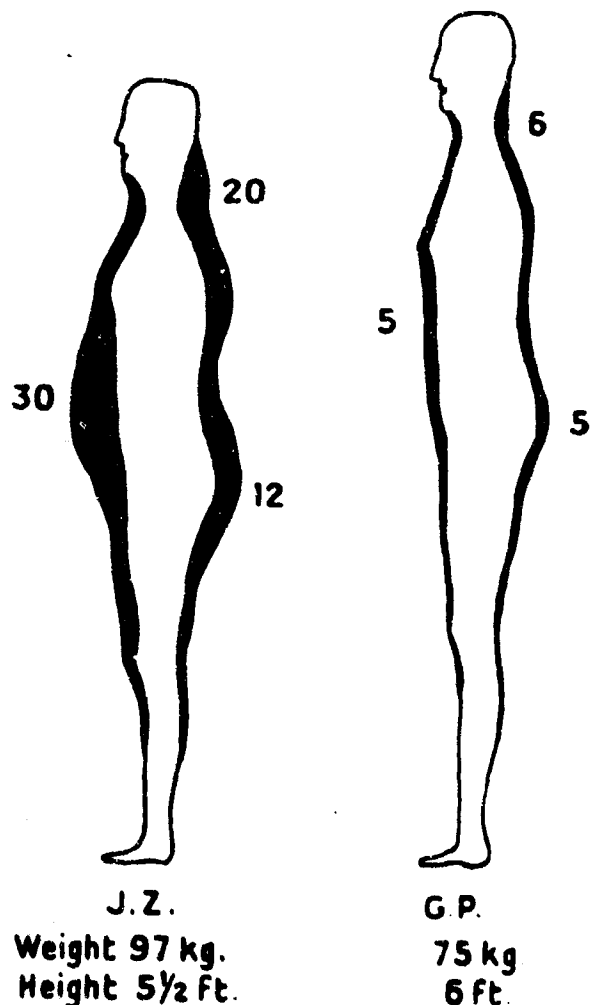


Figure 4. Silhouettes of J. Z. and G. P. Numerals indicate thickness of subcutaneous fat (mm) at the corresponding points. Height of figures is to scale but not thickness of fat. From Pugh and Edholm⁽¹²⁾.

deep body temperatures of J. Z. following the six hour swim in Lake Windermere are plotted against the depth in the subjects forearm and thigh at which the temperatures were obtained. It can be easily seen that the temperature of the deepest tissue, i.e., muscle, approximates that of the rectal temperature and that the tissue temperatures decrease progressively from the core to the skin. These curves imply that this swimmer not only lost heat from his adipose layer but also from his muscle tissue as well. These temperatures are considerably above water temperature, which undoubtedly reflects the high heat output of the muscles during the activity of swimming. Figure 7 shows the deleterious effects upon the body temperature of the thin individual, G. P., when he swam in cold water. In this graph it is apparent that a man of G. P.'s surface area to mass ratio, and with little subcutaneous fat (less than 5 mm) wasn't even able to maintain his body heat when swimming in water at a temperature of 28.3° C (83° F).

The effective thermal conductance and heat productions of these two subjects when swimming in 16° C water and when at rest in a bath at the same temperature are compared in Table III.

It is interesting that both subjects had almost equal metabolic heat outputs while swimming, approximately 600 kcal/hr. However, the layer of adipose tissue which protected J. Z. made the thermal conductivity of his skin and subcutaneous tissue approximately one-half that of his thinner colleague and his tissue insulation twice as effective. As a matter of interest, J. Z.'s effective insulation of .94 CLO would be equivalent to G. P.'s if he were wearing a 1/8" foam wet suit! However, it should not be inferred that J. Z.'s thick layer of body fat provided him with all the necessary insulation required for swimming in cold water, although he thought so. He attempted to swim the Bosphorus when the water temperature was 46° F and swam for four hours. At the end of that time he was semicomatose, had to be taken from the water, and remained in this semicomatose condition for the following three hours. Nor is this the only instance in which channel swimmers succumbed to the cold. Pugh and Edholm reported that the winner of the Ladies Channel Race in 1951 staggered from the water, received congratulations from the judge, and promptly hallucinated about the "furry animals" that had been chasing her on the water! Another channel swimmer was observed to slow his stroke rate markedly and his swimming became almost ineffective. He was taken from the water and it was found that his rectal temperature had dropped to 34° C. He asked for a cotton pledget with which to wipe his eyes and upon receiving it, tried to eat it!

It is important to note that although these channel swimmers were still able to move their limbs in swimming motions, they had lost so much body heat that their brain was no longer functioning normally and they exhibited hallucinations, delusions, and clouding of consciousness. Such insidious cooling of the body, with failure of cerebration preceding failure of locomotion, poses the same type of inherent danger to underwater swimmers that hypoxia does to aviators. These dangers must not be minimized.

From the above considerations it is apparent that hypothermia is a serious problem to swimmers. Moreover, data available to date does not suggest a simple physiological solution to the problem. Increasing the tissue insulation of the body has been proven to be beneficial but this system has limitations too, as determined by the Bosphorus incident. Although a thick layer of adipose tissue is not undesirable for shallow water swimmers (up to 30 foot depth) obesity is currently out of fashion, not only for divers, but for all other service personnel as well.

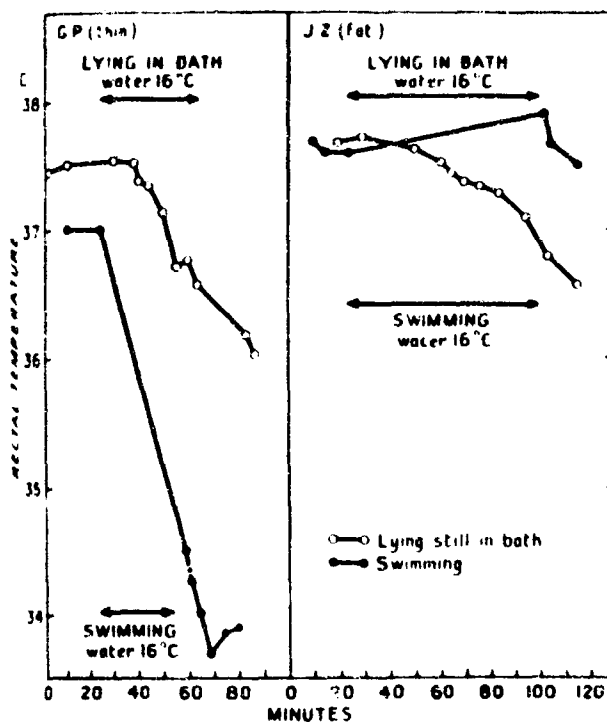


Figure 5. Rectal Temperatures after Swimming and during Immersion without Swimming in Water at 16° C in G. P. (thin) and J. Z. (fat). From Pugh and Edholm(12).

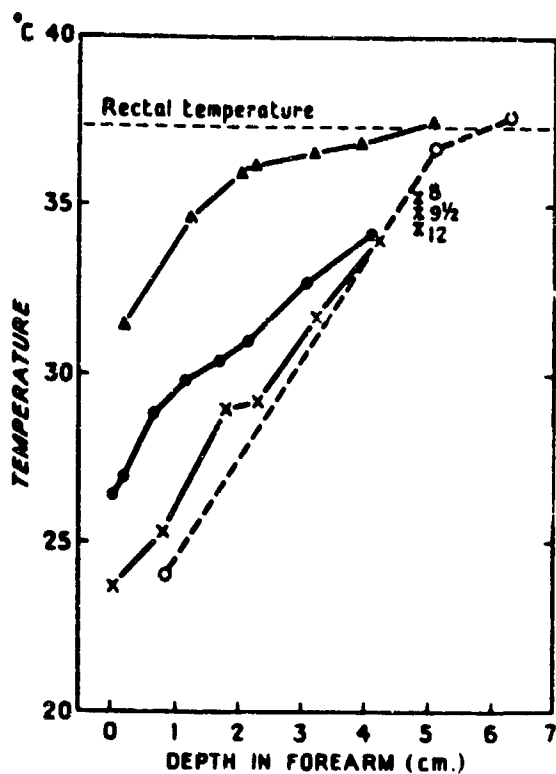


Figure 6. Temperature Gradients in Limbs after Cold Water Exposure. From Pugh and Edholm⁽¹²⁾.

- x — x in J. Z. 's forearm after long-distance swim of 409 min.
- o --- o ditto in thigh.
- — ● in J. Z. 's forearm after 60 min immersion without swimming in water at 16° C.
- ▲ — ▲ in G. P. 's forearm under normal condition.
- ⌘ deep forearm temperature at 8, 9 1/2, and 12 min after leaving the water after 63 min swim.

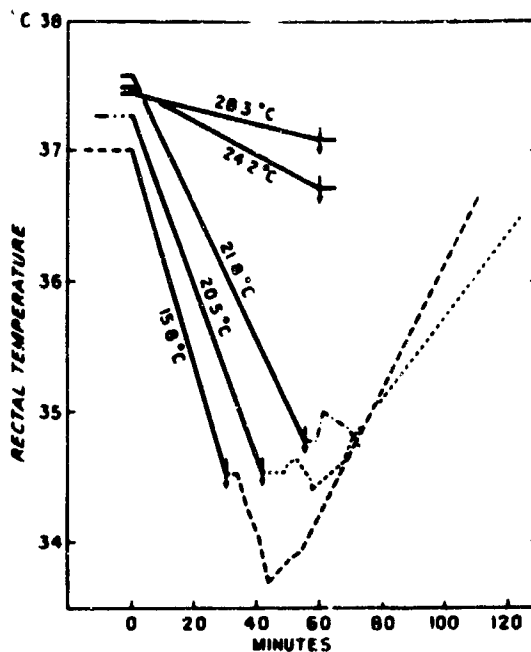


Figure 7. Rectal Temperature in G. P. after Swimming in Water at Various Temperatures. From Pugh and Edholm⁽¹²⁾. Subject entered water at time 0; arrows indicate time of leaving water. The water temperatures are shown above the corresponding rectal temperatures.

Increasing the heat production is the other solution. Although it is possible to increase the muscle mass and efficiency of function by training, the possible improvement in heat production is only of the order of two fold whereas the heat loss is five to eight times normal. The most effective method for maintaining body temperature in underwater swimmers is based

upon preventing heat loss by providing external thermal insulation around the body. The relative values of different insulating materials are listed in Table IV.

The problem of providing adequate thermal protection for underwater swimmers does not have a simple solution. The first significant break through in this area resulted from the proposal by Spealman⁽²⁰⁾ some 10 years ago that a foamed neoprene wet suit would be useful. This unicellular foamed neoprene wet suit for underwater swimming has exceeded its original design specifications and has almost completely eliminated the dry suit for free underwater swimming. The 1/4" wet suit was originally designed to provide sufficient insulation for an underwater swimmer in 32° F water generating 200 kcal/sq m/hr to maintain a skin temperature of 58° F and a normal deep body temperature for one hour. A 3/16" wet suit was designed to provide similar thermal protection in 10° C water.

TABLE III

Effective Thermal Conductance and Insulation
From Pugh and Edholm⁽¹²⁾

	Subject JZ (2.0 sq m)		Subject GP (1.9 sq m)	
	Swimming	Bath	Swimming	Bath
Metabolism (kcal/min)	660	270	630	498+30.8*
Heat dissipated through tissues (kcal/sq m/hr)	290.5	118.8	291.6	261.3
Temperatures				
Skin (°C)	16.0	17.0	25.3	16.0
(°F)	60.8	62.6	77.5	60.8
Rectal (°C)	37.4	37.1	37.1	36.6
(°F)	99.3	98.8	98.8	97.9
Difference (°C)	21.4	20.1	11.8	20.6
(°F)	39.5	36.2	21.3	37.1
Conductance (kcal/°C/sq m/hr)	13.4	5.9	24.7	12.7
Insulation (CLO)**	.42	.94	.23	.44

*Stored heat loss.

**Values for CLO in this table are corrected for error in placement of decimal point in values given in original article.

Field tests of a 1/8" neoprene suit demonstrated the effectiveness of the 1/8" foam suit in protecting swimmers in 50-55 ° F water from significant hypothermia for periods up to 45 minutes⁽¹⁴⁾. Mazzone⁽²¹⁾ carried out field trails of the 3/16" thick, double faced, unicellular foam neoprene suit and demonstrated satisfactory thermal insulation in 56° F water for two hours. Tests of this suit in a dry chamber with an air temperature of -20° F and a wind velocity of four knots demonstrated that 60 minutes was the limit of useful activity under these conditions. This suit had an effective buoyancy at the surface of 15 pounds while at 100 foot depths the effective buoyancy decreased to two pounds.

Additional field tests of a 3/16" unicellular, neoprene, wet suit, a 1/4" unicellular, neoprene wet suit, and the Pirelli type dry suit worn over a 1/4" neoprene, wet suit are reported by Martorano⁽²²⁾. In these tests, the subjects remained essentially motionless while immersed up to neck level in water of 35.4° to 37.8° for periods up to 30 minutes. Temperature measurements were made on the skin of the upper arm, over the back of the scapula, on the chest, on the lateral aspect of the thigh, on the tip of the index finger, and on the great toe.

TABLE IV

Thermal Conductivity of Various Materials

Material	Thermal Conductivity (kcal/sq m/hr/°C per cm thickness)	Reference
Still air	2.3	14
Wool clothing (normal)	8	14
Wool clothing (maximum)	3.4	14
Foamed neoprene*	4.6	14
Solid neoprene or rubber	16	14
Rubber impregnated cloth	16	14
Body, fat	14.4	13
Muscle (wet)	39.6	13
Water	53	14

*Calculated on basis of additive conductivity of neoprene and nitrogen gas.
Density of neoprene taken as 1/8 gm/cu cm 0.156 normal density.

Core temperatures were determined by rectal temperature measurement. In these tests the critical skin temperature for cooling of the hands was set at 55° F since the skin of the fingers became numb and sensation of touch and pain were lost with increasing muscle weakness below this temperature. As can be seen in Figure 8, the skin temperature of the fingers decreased to critical values in one-half hour when subjects were wearing the 3/16" wet suit and in one hour when wearing the thicker 1/4" suit. The addition of a dry suit over the wet suit did not significantly decrease the rate of cooling.

The difficulty of providing adequate insulative covering to the hands, feet, and fingers was emphasized in Arctic field clothing research in World War II. Some of the findings of these investigations are described^(18,23). The geometrical dilemma of finger clothing is graphically shown in Figure 9, in which the effectiveness of insulative materials in CLO units is shown for plane surfaces, cylinders, and spheres. This graph shows why it has been said that to provide 4 CLO insulation for the fingers, the fabric thickness would have to be 3.5 inches. This graph also shows that no practical glove insulation can be constructed greater than 1 to 1.2 CLO. This would be approximately the CLO value of a foamed neoprene glove 1 cm in thickness. The result of research and field experience on Arctic clothing reported from the U.S. Army Climatic Research Laboratory is quoted by van

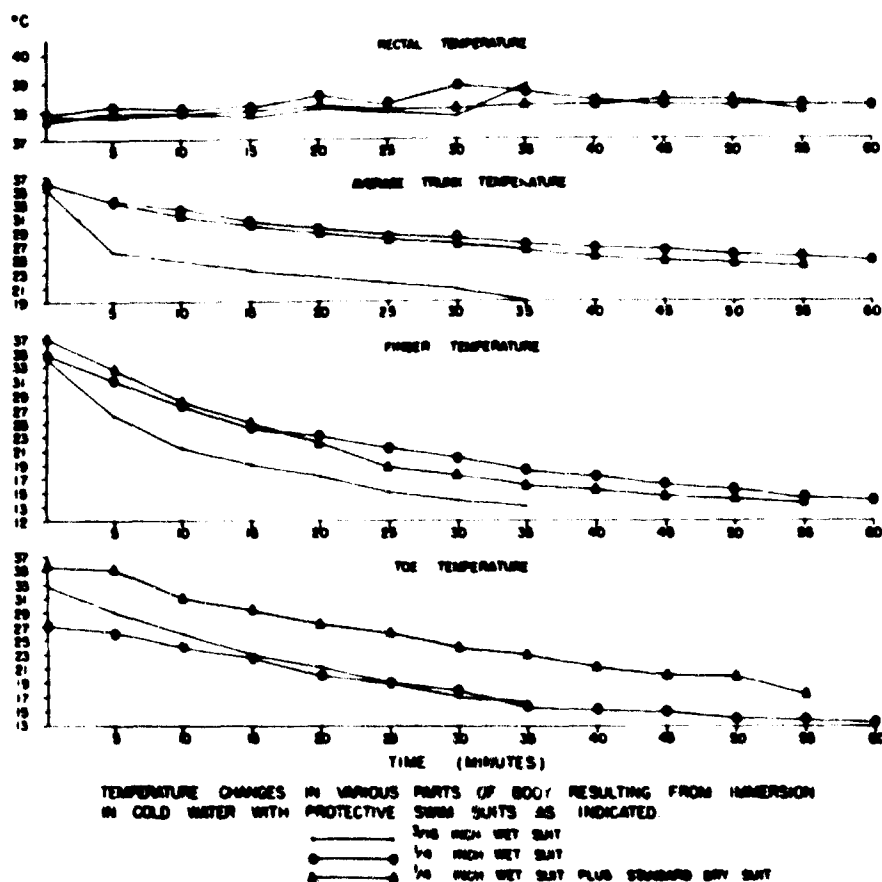


Figure 8. Temperature Changes in Various Parts of the Body Resulting from Immersion in Cold Water with Protective Swim Suits.

Dilla(18) as follows: "The hands cannot be kept warm in Arctic environments except by maintaining a rapid circulation of blood (by exercise), by withdrawing the hand and arm into a parka type shirt or by artificial heat." These same observations are applicable to hypothermia from water immersion as well.

The unicellular neoprene wet suit therefore would seem to have some limitations, despite its many advantages. These disadvantages were to be expected. The original calculations on the development of the wet suit were based upon a desired skin temperature of 58° C. The "comfortable" skin temperature has been demonstrated to be 34-35° C(24). Somewhat lower skin temperatures are comfortable during exercise in water. Indoor swimming pool temperatures are generally kept at 80° or slightly above for optimal competitive swimming. Rarely are temperatures as low as 74° F used. Consequently, since the purpose of insulative clothing for swimmers is to maintain optimal function, the heavy foam wet suit should be designed to permit a comfortable skin temperature (80-84° F) when swimming in water at 28° F, the freezing point of sea water. To provide such protection, the wet suit would have to have a mean thickness of

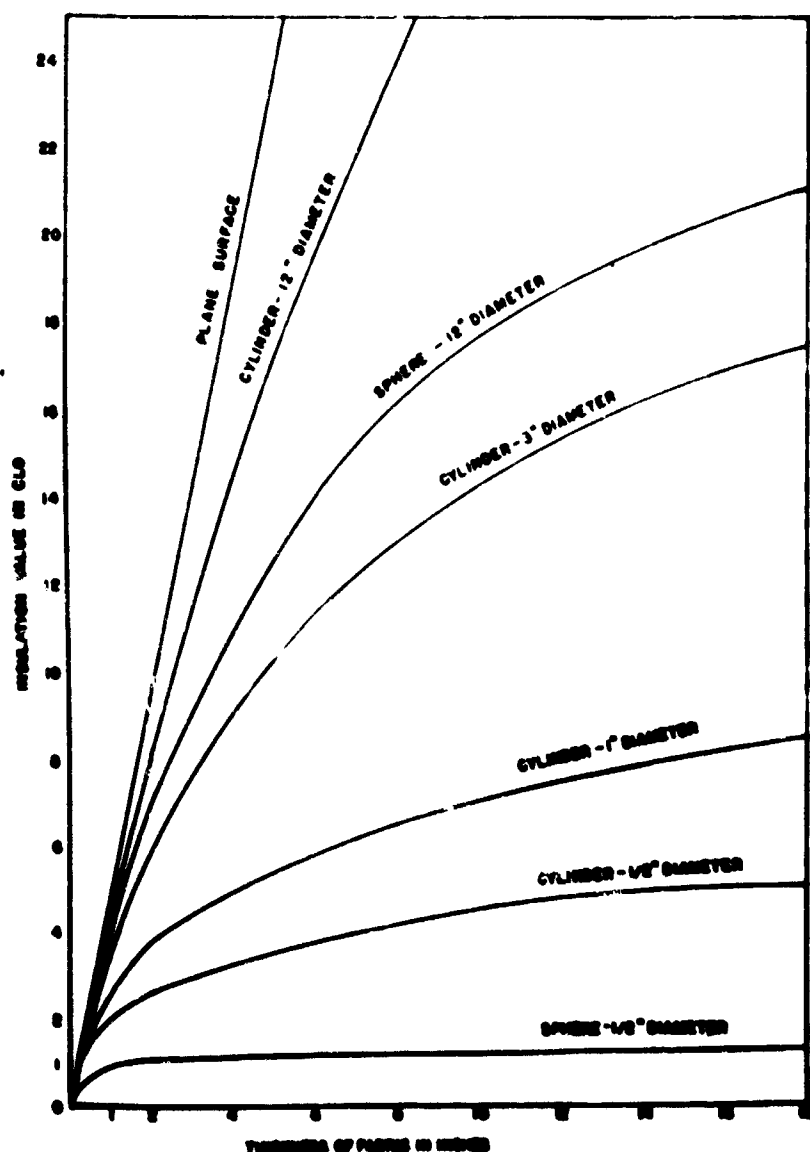


Figure 9. Insulation of Ideal Fabric on a Plane, Cylinders and Spheres. From van Dilla, *et al*⁽¹⁸⁾.

decline with each succeeding hour and the body temperature would also fall. The exact heat deficit which any given swimmer would develop cannot be predicted accurately. In general, it would be expected to be between 100 and 200 kcal per hour and would increase gradually during the period of hypothermia if the muscle mass was cooled and decreased its heat output. An average heat debt of 200 kcal/hr for extremes of water temperature must therefore be expected.

Even though a 1/2" wet suit would satisfactorily insulate the cold-water swimmer operating at a 10 to 15 foot depth, its buoyancy would present a problem if the diver were to change depths. The greatest part of the insulation provided by foamed neoprene is based upon its trapped air. The volume of this trapped air, and therefore the buoyancy and the insulation of the suit, are inversely proportional to the water pressure. The thickness of unicellular, foam, neoprene, wet suits was found to decrease as the pressure increases (Figure 10). Tests of a 1/8" wet suit gave a buoyancy of nine pounds on the surface and six pounds at 35 feet. An average swimmer, using a 3/16" wet suit, required 18 pounds of lead weights for ballast on the surface and the same swimmer using a 1/4" unicellular foam

approximately 0.5 inches or twice the thickness of present heavy wet suits. Even this thickness of foamed neoprene would not provide adequate insulation for the hands for work in 28° F water.

A 1/2" wet suit could, of course, be fabricated, and SCUBA divers have been known to wear two 1/4" foam wet suits in an attempt to retain body heat. However, a suit of this thickness becomes too bulky to wear. In addition, the original calculations for the wet suit stipulated a heat supply from the body of not less than 200 kcal/sq m/hr. This would be a total heat output of 380 kcal/hr for the average 70 kg man. This would be approximately the oxygen consumption found by Hoff, *et al*⁽²⁵⁾ to be utilized for maintaining a pace of 1 knot for one hour when swimming with fins. Maintaining this work output for 2, 3 and 4 hours would become progressively more difficult, so that the heat generated by the body would

wet suit required 28 pounds. The change in buoyancy which occurs when an underwater swimmer wearing a foam, neoprene wet suit changes his swimming depth is shown in Figure 11. This decrease in insulation and buoyancy with depth is undesirable, and limits the usefulness of the wet suit for diving at depths. The foamed neoprene wet suit concept of thermal protection for underwater swimming has greatly increased the cold water tolerance time but it still has some deficiencies.

Present developments in diving equipment suggest that divers and underwater swimmers will have available greatly increased bottom times. The development of improved gas mixtures will likewise increase the operating depths of divers. Improved systems of protecting divers from general and localized hypothermia for long periods of time without buoyancy penalties are therefore required.

The requirement exists to provide a system to supplement the heat output of the underwater swimmer wearing

a wet suit under the following conditions: 1) whenever he stops swimming or working; 2) whenever he swims to greater depths; 3) whenever he must stay submerged for longer than one hour; and 4) whenever maximum manual dexterity is required or whenever cooling of his hands and fingers limits the operational mission.

In order to support a swimmer for a 4 to 6 hour dive in 28 to 40° F water it will be necessary to provide him with approximately 200 kcal/hr additional for 4 to 6 hours. It is anticipated that this external heat source could be readily provided by the use of a resistance wire, thermal suit to be worn under the foamed wet suit or incorporated within its thickness. The present state of the art of battery power suggests that rechargeable batteries could be used which would provide the necessary power to a resistance type thermal suit so as to provide approximately 1 kilowatt hour. Inasmuch as underwater swimmers must wear approximately 15 to 28 pounds of lead weight to compensate for the buoyancy of the foam rubber suit, it would seem logical to replace this inert ballast with a similar weight of electric batteries which could serve both as ballast and a source of electric power. Preliminary calculations on the feasibility of such a suit and preliminary measurements indicate that both the heat requirements and the weight

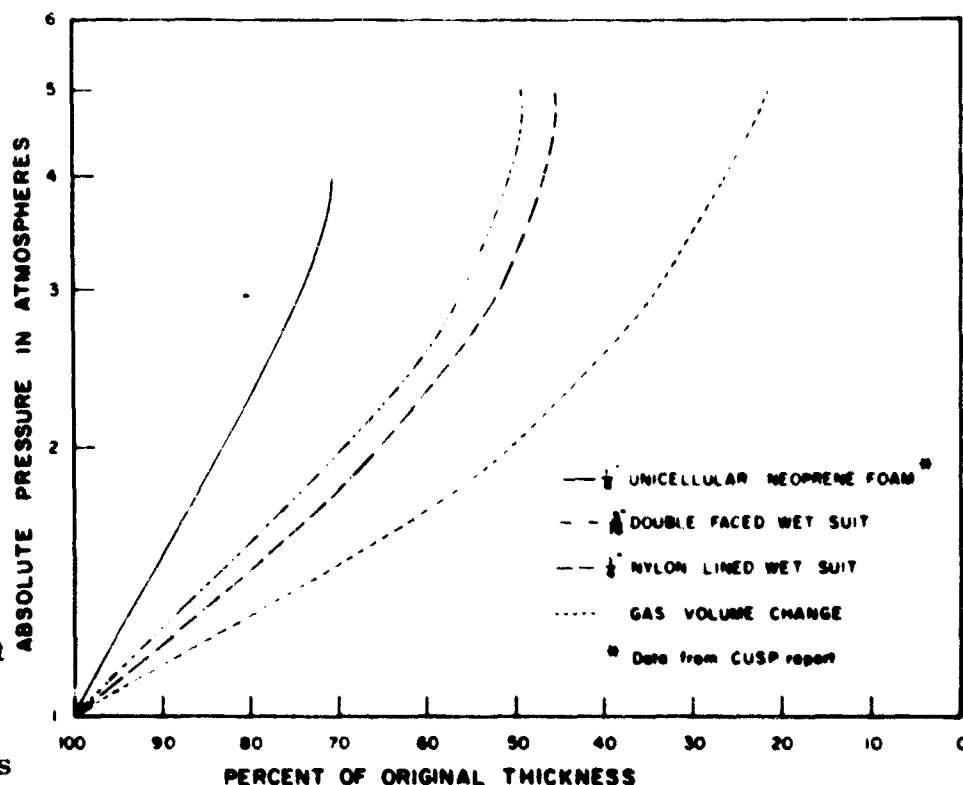


Figure 10. Per Cent Change in Thickness of Unicellular Foam Rubber Swim Suit with Depth.

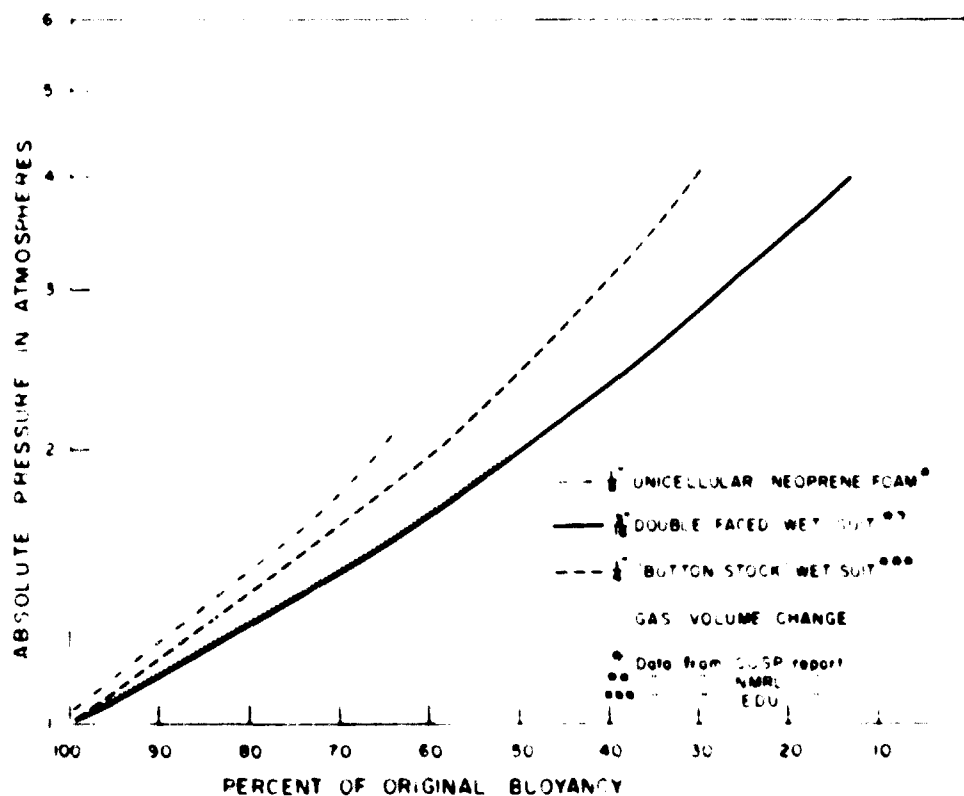


Figure 11. Per cent Change in Buoyancy of Unicellular Foam Rubber Swim Suit (including boots, hood and gloves) with Depth.

swimmer. Likewise, the pulmonary heat loss due to evaporation from the lungs and to heating of the inspired air (15-24 per cent of heat production) can be prevented by warming and humidifying the inspiratory air supply. This is technically feasible and would be physiologically beneficial.

In addition to the electric resistance wire system for supplying heat, exothermic chemical or physical processes could undoubtedly be developed which would supply the requisite amount of heat as well.

limitations can be met by an electrically heated suit, powered by rechargeable (silver-zinc) batteries.

In addition to providing a supplemental heat source for maintaining the mean temperature of the skin and deep tissues, an electrical system could also provide differential heating to the hands, feet and the head. Such a system for providing supplemental heat to the hands is particularly needed and could be under the control of the

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